

Review of Monte Carlo methods for particle multiplicity evaluation

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Abstract. I present a brief review of the existing models for particle multiplicity evaluation in heavy ion collisions which are at our disposal in the form of Monte Carlo simulators. Models are classified according to the physical mechanisms with which they try to describe the different stages of a high-energy collision between heavy nuclei. A comparison of predictions, as available at the beginning of year 2000, for multiplicities in central AuAu collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and PbPb collisions at the CERN Large Hadron Collider (LHC) is provided.

1. Introduction

Heavy Ion Physics is a very complex field. Many different physical mechanisms have to be considered to describe a high-energy collision between heavy nuclei. The available Monte Carlo tools in the form of simulators, see the reviews [1, 2], are already quite sophisticated but not yet so standardized and developed as the corresponding ones in hadron-hadron collisions. The reason for this is, of course, the complexity of the field.

The central goal of Heavy Ion Physics in the production and characterization of a new phase of matter, the Quark Gluon Plasma (QGP), in which deconfinement and chiral symmetry are restored. In this way we expect to gain a basic understanding of these still poorly known, key features of the field theory of strong interactions, Quantum Chromodynamics (QCD). But even without the presence of any phase transition, our understanding of a high-energy collision involving nuclei is far from being complete. While we have theoretical control on perturbatively computable quantities, non-perturbative effects are dealt with by models. Many of these non-perturbative effects get enhanced by the nuclear size. The density of produced particles leads to possible non-linear effects of much less importance in hadron-hadron collisions. Obviously the possibility of phase transitions makes the task of describing a heavy ion collisions even more involved. So the standard procedure for hadron-hadron collisions: hard collisions (+ radiation) + hadronization + underlying soft event has to be reconsidered, and many models have appeared through the years. At variance with hadron-hadron were little attention is paid to the time evolution of the collision, a space-time picture is assumed implicitly or explicitly in the models which aim to describe heavy ion collisions.

The demands to a Monte Carlo event generator are gigantic: they are supposed to give full information about the event, so they must deal both with hard probes (jets, heavy flavors,...), under theoretical control in perturbative QCD (pQCD), and the underlying soft event, model-dependent and, at most, inspired in QCD. Total multiplicities correspond to the latter. Another

point which should be stressed and which makes the task of event generator even more demanding is the fact that sometimes the underlying event is not only the background (for jet quenching, charmonium suppression,...) but the signal itself (strangeness, correlations, interferometry, flow,...). The simplest approach of a superposition of nucleon-nucleon collisions fails, so some degree of collectivity (or interference) is introduced in most models. Simple superposition is taken as a baseline. The key question to answer is whether this collectivity corresponds to a fully thermalized QGP, in which case the models should provide the initial condition for such state and justify the way to thermalization, or to a non-thermalized system. In any of these two cases, the applicability of the models has to be seriously examined.

In this review I will consider each simulator as a distinct model. Many simulators use the same 'physical' model to describe some stage of a heavy ion collision. But even in this case both the details of the implementation of the model – even the apparently most obvious ones like energy-momentum conservation – and the different description of other stages of the collision, vary from model to model. Besides, model parameters are tuned to 'final stage' experimental data. As a result the predictions of the models differ even when they claim to be implementations of the same physics.

Let us have a look to the situation in December 1995 as presented in [3]. In Fig. 1 differences of a factor ~ 4 can be seen between the model which contains collectivity (lowest line at $\eta = 0$) and all the other models which do not include collective effects. But even among the latter differences of a factor ~ 2 can be observed. Actually it was this study which led to the strategy of the LHC experiments to make the simulations in two extreme scenarios, namely 8000 and 2000 charged particles per unit rapidity at $\eta \simeq 0$ for the background in a central PbPb event. We will see that experimental data coming from RHIC tend to favor those models which the lowest multiplicities, but uncertainties of a factor ~ 2 still exist.

This paper is organized as follows: in the next Section a classification of models is offered, together with an enumeration and a brief summary of their main characteristics. Any possible omission has not been deliberate but it is due to my ignorance, for which I anticipate my excuses. In Section 3 predictions from different models for charged multiplicities in central collisions at RHIC and the LHC as available in February 2000 [2] – the situation before RHIC started its operation in June 2000 – are reviewed. I consider this exercise more informative than digging into more recent post-dictions which, obviously, reproduce RHIC data. Finally I present some conclusions.

2. Classification of models

A classification of models for heavy ion collisions is always delicate, due to the fact that most models are mixed models: They contain different physical assumptions for each stage of the collision. Here I have tried to use the stages of a heavy ion collision to offer some guidance (as done in [4]), see Fig. 2. Models will be classified according to what I understand is their main emphasis. Saturation [5, 6] (no yet available in the form of a Monte Carlo simulator), parton cascade and string models intend to describe the initial stage, usually called pre-equilibrium when one assumes that equilibration will occur. They are further extended to subsequent stages when no equilibration is assumed. The equilibrated partonic stage (QGP) is described by hydrodynamics or statistical models, which can be extended to describe the last stage (hadronic phase). Hadron transport is only intended to describe this last stage, but hadronic models exist which try to simulate the whole history of the collision. For a longer discussion on and description of the different models and their options, please have a look to [2].

2.1. Hadronic models

Hadronic models consider the description of the nuclear collisions through the simple superposition of hadron-hadron collisions. The number of such collisions for a given impact

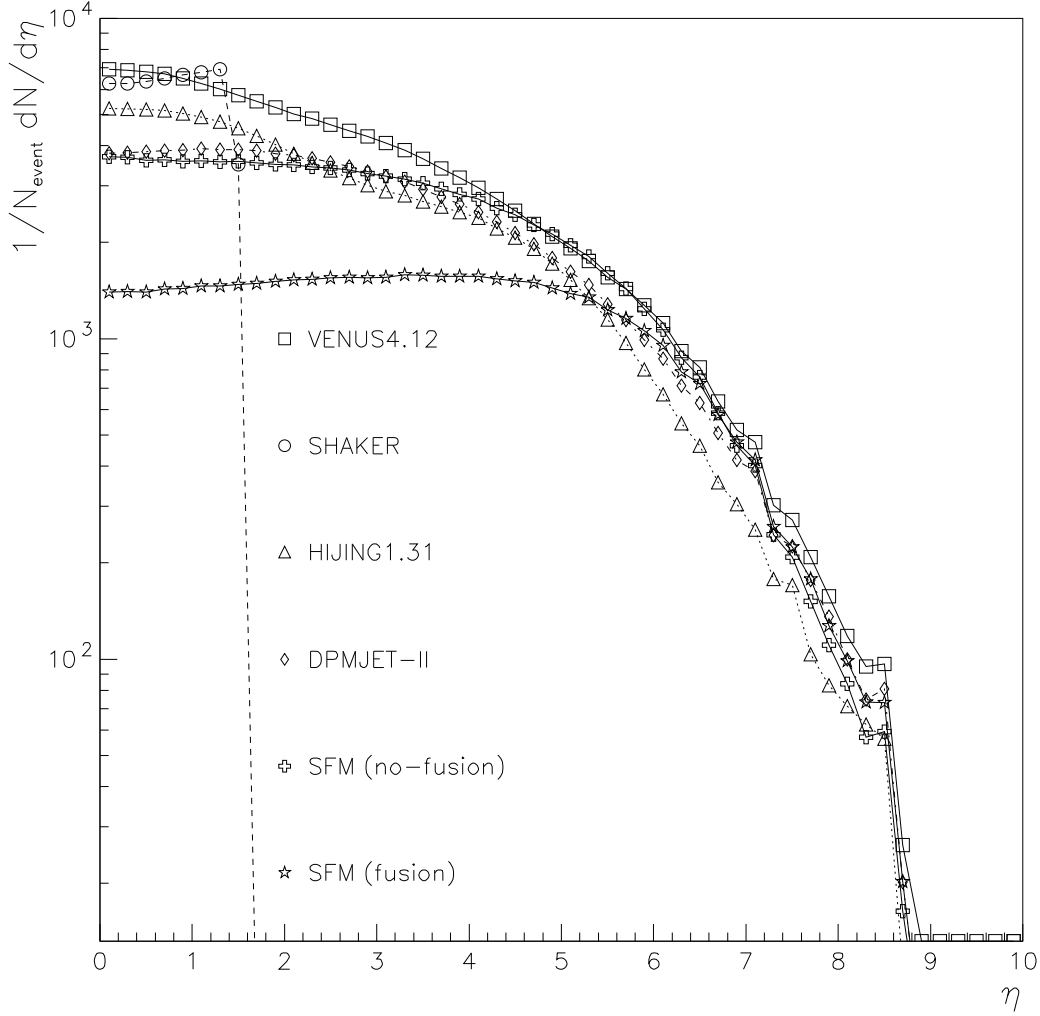


Figure 1. Predictions from different models for the charged pseudorapidity density in central ($b \leq 3$ fm) Pb-Pb collisions at $\sqrt{s} = 6$ TeV per nucleon, from [3].

parameter b is determined by nuclear geometry using the Glauber-Gribov model [7, 8]. Both LUCIFER [9] and LEXUS [10] belong to this category. The latter is used as a baseline: The failure of this approximation means the onset of collective effects among several nucleon-nucleon collisions.

2.2. Parton cascade models

In these models, a relativistic Boltzmann equation is solved for partons. Cross sections and splittings are computed in pQCD at lowest order. The initial conditions are provided by either a nuclear wave function like in VNI [11] or PCM [12], or by partons produced in initial parton-parton collisions in AMPT [13] (as provided by HIJING, see below). Initial and final state radiation, coherence of the initial state and the possibility of hadronization via coalescence is included or under consideration in PCM.

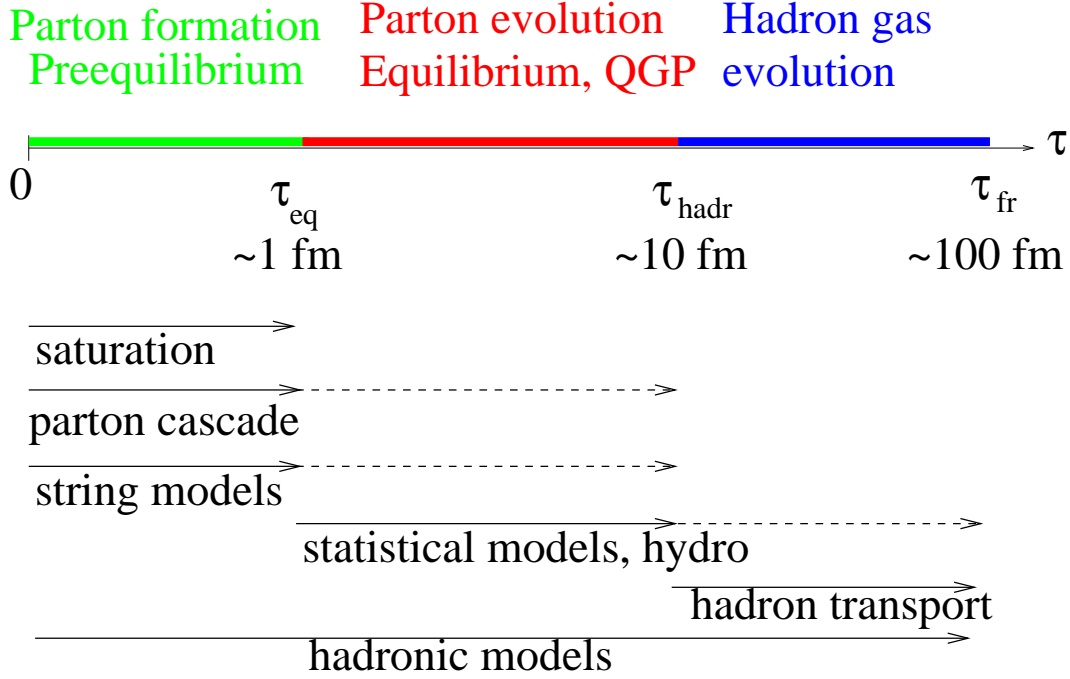


Figure 2. Schematic cartoon of the stages of a heavy ion collision and of the models which try to describe every stage. Solid lines indicate the stages for which the models were initially designed. Dashed lines indicate the stages to which sometimes they are extended. Time scales are merely indicative of orders of magnitude.

2.3. String models

String models describe the collision through the exchange of color or momentum between partons in the projectile and target. As a consequence of these exchanges, these partons become joined by colorless objects, which are called string, ropes or flux tubes. These models were originally designed for hadron-hadron, its generalization to hadron-nucleus and nucleus-nucleus done through the Glauber-Gribov theory [7, 8]. Hard collisions (i.e. pQCD computed parton-parton collisions) are included, so these models contain a soft and a hard component which is crucial for their application to RHIC and LHC energies. Models of this type are HIJING [14], PSM [15], DPMJET [16], NEXUS [17] and LUCIAE [18]. VENUS [19], Fritiof [20] and the SFM [21] are no longer maintained.

Strings are used as initial stage in some transport models (RQMD, UrQMD and HSD, see below), and as the fragmentation method in most models. Some collective mechanisms have been introduced, as pomeron interactions in DPMJET or NEXUS, high-color fields or string fusion in PSM, HIJING, RQMD, LUCIAE and DPMJET, and increased stopping through baryon junction migration in HIJING and DPMJET. Jet quenching has also been introduced in HIJING.

2.4. Hydrodynamical/statistical models

In this item I include those models which assume local thermodynamical equilibrium at a partonic level. Among the models which consider a hydrodynamical evolution of a QGP, some of them emphasize the phase transition [22] to hadronic matter linked to hadronic transport by UrQMD while others consider an initial condition given by HIJING or saturation [23] (introducing also jet quenching inside the plasma). The statistical models in which hadronization is determined by phase space, are now available in Monte Carlo form [24].

2.5. Hadron transport models

In these models, a relativistic Boltzmann equation is solved for hadrons in the final stage of the collision (after hadronization). A huge variety of hadron species and of cross sections is introduced. These models are AMPT, RQMD [25], UrQMD [26] and HSD [27]. Besides, simple models for rescattering of secondaries and spectators have been introduced in LUCIAE, DPMJET and PSM to explain some experimental data like multi-strange baryon enhancement.

2.6. Comments

Here I will make some comments on the general status of the models:

- Physically there is no clear border between one stage in a heavy ion collision and the previous or the subsequent one: the division between the different stages is indeed artificial. Also this division implies that causality and some factorization hold. This is assumed but not at all guaranteed.
- Energy-momentum conservation is a key demand for all the simulators, but it is not so easy to fulfill. Usually this means no difficulty for RHIC and LHC energies, but may be problematic for the most massive nuclei at smaller energies.
- Models are designed to describe the full event, not just one of the stages. Parameters are tuned to experimental data, which demands some modeling or assumption about the whole history of the event. So most models are multi-step ones, containing different pieces corresponding to the different stages linked one each other.
- Only DPMJET, HIJING and PSM work for LHC energies (they are included in the ALICE Generator Pool [28]).
- Codes are written in Fortran, not in C++. Little standardization exists, e.g. few of them follow the OSCAR protocols [29].
- Pieces of PYTHIA [30], ARIADNE [31] and JETSET [32] are used in many codes. Charm and beauty production is usually introduced through PYTHIA.
- Predictions for LHC should be constrained by RHIC results but are still uncertain in a factor ~ 2 , due to existing open questions on the small- x behavior of parton densities, the degree of collectivity achieved in the collision, the existence or not of the QGP,...

3. Predictions for RHIC and LHC (as available in February 2000)

A comparison of experimental data with some available Monte Carlo codes is done in almost every experimental paper. Many of them can be found in the experimental talks at this Workshop. For example, [33] contains an extensive comparison of model results for multiplicities at central rapidity and their centrality evolution at RHIC energies. So instead of looking into the recent modifications of models to reproduce RHIC data, I will concentrate in analyzing the situation in February 2000, previous to the first RHIC data (the first collisions at RHIC happened in June 2000).

Most of the results presented here come from the review [2], see there for a description of the models and full references. In that review results from many models for RHIC and LHC are compiled. But predictions from the models have been given for different conditions: centrality cuts done through impact parameter or percentages of the cross sections, slightly different energies, AuAu or PbPb collisions both for RHIC and the LHC, η or $y \simeq 0$,... In order to present them in a compatible manner, I have corrected each result to the common conditions: 5 % most central collisions at $y = 0$, for AuAu at 200 GeV per nucleon (RHIC) and PbPb at 5.5 TeV per nucleon (LHC), using an early version of the Monte Carlo [15]. In [2] you can find tables containing the published predictions of the different models and the correction factors, which were found to be as large as 20 % for RHIC and 17 % for LHC. This procedure could

only be done properly inside each model, so a systematic uncertainty of $10 \div 15$ % has to be understood.

Predictions from seventeen models will be presented in the following Subsections. Not all of them are available both at RHIC and at the LHC. Let me briefly indicate the models which ones are contained in the following figures:

- (i) DPM [34]: a version of the Dual Parton Model including shadowing corrections due to pomeron interaction diagrams.
- (ii) DPMJET [16].
- (iii) SFM: an early version of [15] which is an evolution of [21].
- (iv) RQMD [25].
- (v) HIJING [14]: versions of HIJING with and without jet quenching give differences for multiplicities of about a factor 2 for LHC; the value I indicate in an average of the results with and without quenching.
- (vi) Eskola *et al.* [35]: a model containing saturation.
- (vii) HIJING+ZPC+ART, now called AMPT [13].
- (viii) UrQMD [26].
- (ix) VNI+UrQMD as contained in [1].
- (x) Hydro+UrQMD [22].
- (xi) VNI+HSD as contained in [1].
- (xii) VENUS [19].
- (xiii) NEXUS [17].
- (xiv) Statistical [1]: obtained from the results of the statistical model presented in that reference.
- (xv) WA98 extrapolation [36]: extrapolation of low energy results done by the WA98 Collaboration.
- (xvi) WNM: a simple extrapolation [2] to nucleus-nucleus from nucleon-nucleon done in the Wounded Nucleon Model.
- (xvii) Percolation: a simple estimate [2] in the framework of percolation of strings [37].

I will mainly discuss the results of those models available as Monte Carlo simulators.

3.1. RHIC

In Fig. 3 the results from different models for RHIC (charged particle multiplicity per unit rapidity at $y = 0$ for 5 % most central AuAu collisions at 200 GeV per nucleon) are presented and compared with experimental data. The red lines define a band where the central values for charged multiplicities provided by RHIC experiments lie (see [33] and references therein). These experimental values have been corrected in the same way, previously explained, as the results from different models.

It can be observed that low multiplicities are favored, which indicates a high degree of coherence or interference. Models without collectivity tend to give too large values. In order to lower the multiplicities, now HIJING has included a large gluon shadowing [38] and DPMJET considers percolation of strings [39].

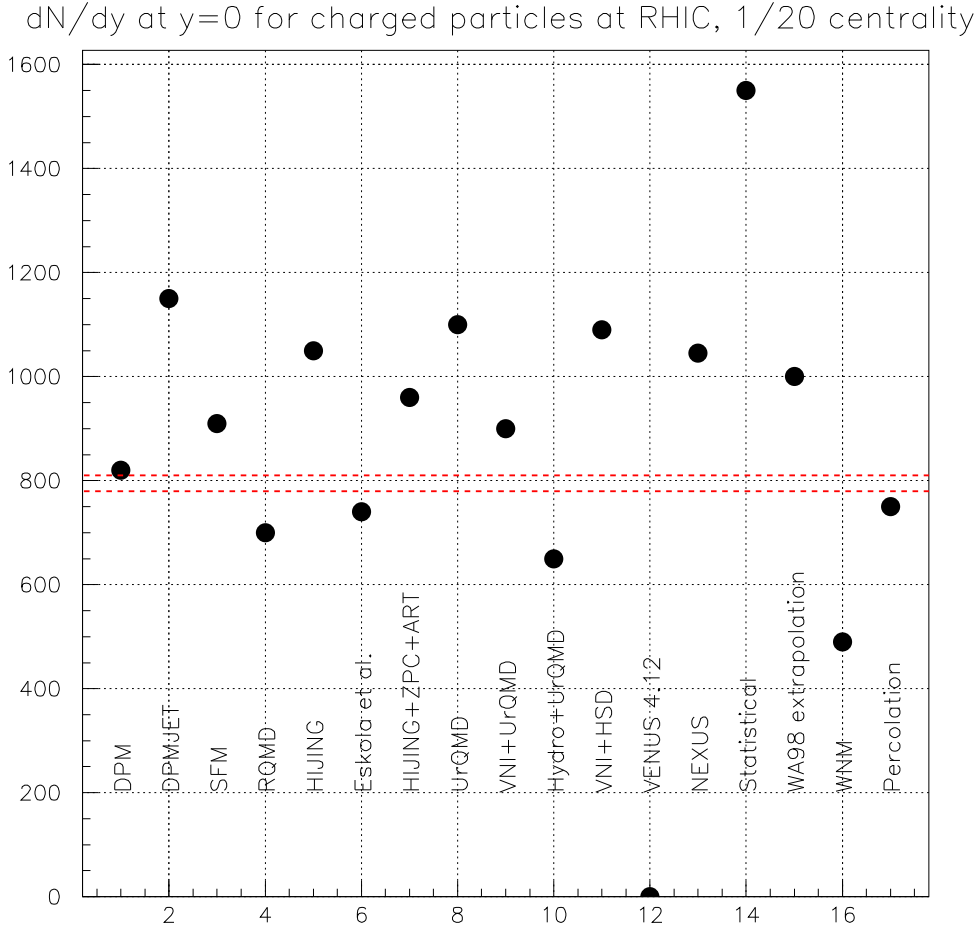


Figure 3. Results from different models for charged particle multiplicity per unit rapidity at $y = 0$ for 5 % most central AuAu collisions at 200 GeV per nucleon. Models are explained in the text. The red lines are only to guide the eye and correspond to experimental data, see the text.

3.2. LHC

In Fig. 4 the results from different models for LHC (charged particle multiplicity per unit rapidity at $y = 0$ for 5 % most central PbPb collisions at 5.5 TeV per nucleon) are presented. The red lines correspond to averages of the results of models: The top line corresponds to all models but WNM and percolation (which are most naive estimations). The line in the middle corresponds to all models but WNM and percolation, and VENUS (which is no longer maintained and gave the largest prediction already in [3], see Fig. 1). And the lower line corresponds to all models but WNM, percolation and VENUS, and HIJING and statistical (in order to produce some kind of average for the models predicting the lowest multiplicities, which seem to be favored by RHIC data).

It can be seen that low multiplicities, $2000 \div 4000$, are now favored. But even with RHIC constraints, uncertainties of a factor ~ 2 persist, as anticipated. Saturation [5, 6] and percolation

of strings [40, 41] predict multiplicities ≤ 2000 . On the other hand, predictions from HIJING without quenching, ~ 5000 , and with quenching, ~ 9000 , vary almost a factor 2.

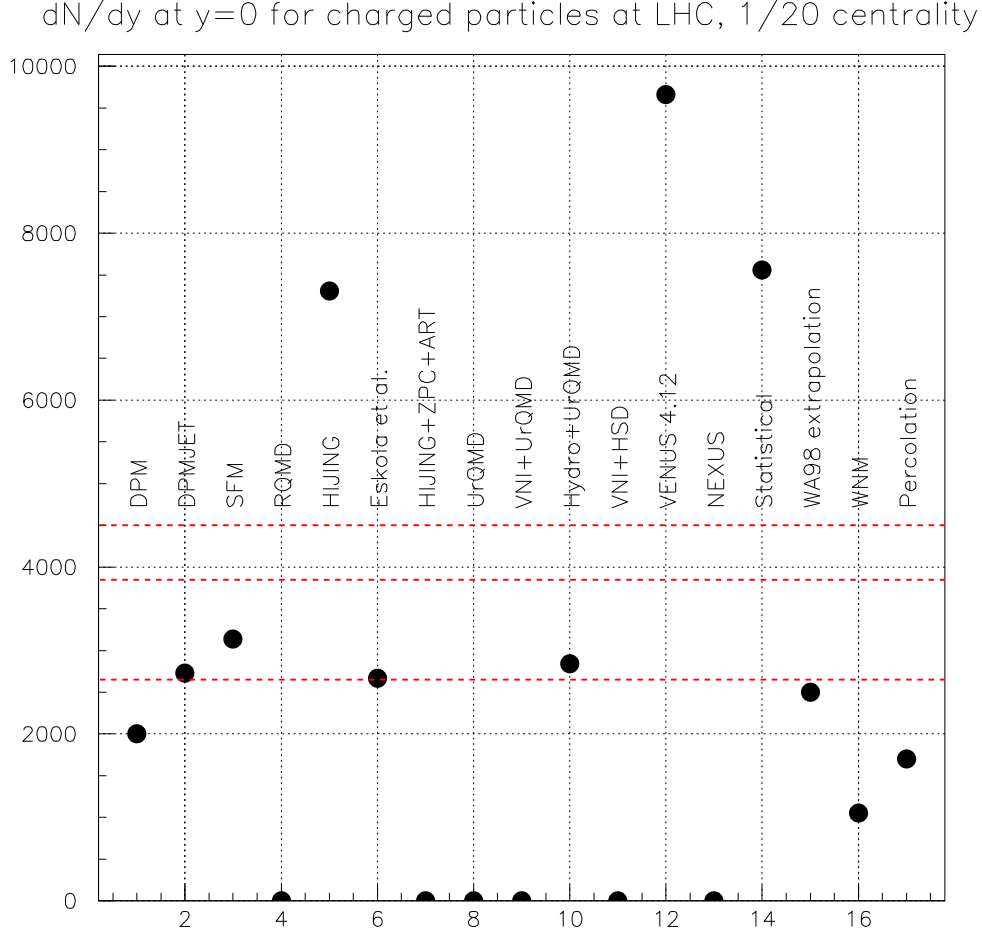


Figure 4. Results from different models for charged particle multiplicity per unit rapidity at $y = 0$ for 5 % most central PbPb collisions at 5.5 TeV per nucleon. Models are explained in the text. The red lines are only to guide the eye and correspond to averages of models, see the text.

4. Conclusions

In this paper I present a brief review of the existing Monte Carlo tools to simulate heavy ion collisions at ultra-relativistic energies. Some of them: PSM, DPMJET and HIJING, are already available [28] for heavy ion collisions at the LHC. Let me present some personal comments:

- With constraints coming from RHIC, low multiplicities at LHC, $2000 \div 4000$, seem to be favored.
- Collectivity is a well established phenomenon, but practical realizations differ both conceptually and quantitatively.

- At RHIC and LHC energies, a description of the initial stage in terms of partons, not hadrons, looks unavoidable.
- Constraints from RHIC reduce basic uncertainties for LHC but some of them still remain, e.g. multiplicity reduction or transverse momentum spectra. This is mainly due to the fact that RHIC is pre-asymptotic compared with theory and with the energy available at the LHC.
- Producing a Monte Carlo simulator demands a large effort which extends through several years. Some of the existing models are or will be ruled out by RHIC data, others will simply extinguish. The interplay between simulator builders and experimentalists is crucial for the former to keep on creating and updating their codes. While new models are under production for hadron-hadron at the LHC, to my knowledge no new model is currently under construction for the corresponding heavy ion collisions.
- The actual problems for RHIC are mainly transverse momentum distributions in AuAu collisions compatible with those in dAu (see [39, 42]), and elliptic flow (see [43, 44]).
- Models contain different decoupled stages. A better theoretical understanding of such decoupling assumption is needed.
- Codes are not standardized (compared to hadron-hadron simulators). The lack of a reliable, generally accepted theoretical baseline makes it difficult to establish long term programs. Increasing modularity as proposed by the OSCAR protocols [29], with the possibility to link different initial stages to different models for thermalization or intermediate transport and hadronic cascades, would offer new opportunities for model building.
- Interplay with the Cosmic Ray Physics community is possible and highly desirable [45].
- Hard probes like jet quenching, for which we have reliable theoretical understanding, must be included in a simulation of the whole event. Even with a rough knowledge of the underlying event, this would be a great help. Also saturation and phase transitions like that from QGP to hadronic matter or percolation have to be considered as options.
- The problems of detailed balance and Lorentz invariance in parton cascades are still open questions. For example, the inclusion of $2 \rightarrow 3$ processes is argued [46] to make a huge difference in thermalization times within a parton cascade.

Let me finally comment that looking from outside our field, the status of Monte Carlo event generators for heavy ion collisions may look still at the beginning. There are many open fundamental questions which are theoretically accessible but not yet solved completely. But it should not be forgotten that not all interesting questions demand such precision as is intended in hadron-hadron. Even simple implementations of the underlying event may provide valuable conclusions. And, plasma or no plasma, there is a lot to learn which is equally valuable for hadron-hadron.

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